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THE BASICS of WEATHER MODELS

by

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AWS/XTX

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This forecaster memo (FM) summarizes the history and fundamentals of modern numerical weather prediction models for operational weather forecasters. The information is intended to help forecasters understand the models' strengths and weaknesses. It is published with the expectation that an increased understanding of the details of these complex mathematical models will help forecasters make better use of NWP model forecasts. The FM complements information in Chapter 7 of AFP 105-56, *Meteorological Techniques*. The author would like to thank Lt Col James Davenport, Chief of the Product Improvement Division, HQ Air Weather Service, for suggesting the topic. He would also like to thank Lt Col Edwin Jenkins, Deputy Director of Technology, HQ Air Weather Service, for his assistance in publishing the memo. Thanks also to Mrs Mary Fulton for typing the manuscript.

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THE BASICS OF WEATHER MODELS

INTRODUCTION

Without using mathematics, this memo summarizes the important information weather forecasters need to know to apply numerical weather prediction (NWP) forecasts. We've had to make some tough choices regarding what material to include. We've put the more technically rigorous information in an appendix; readers can review this material as they have time. We've organized the material under three main topics:

- *History of NWP.*
- *Components of an NWP model.*
- *Strengths and weaknesses of NWP models--what these models can and cannot do.*

HISTORY OF NWP

Meteorology has been described as the second most complex science; medicine being the first. Nevertheless, a set of mathematical equations that completely describes the behavior of the atmosphere has been known since early in the nineteenth century. During World War I a British meteorologist-mathematician-statistician by the name of L. F. Richardson attempted to use these equations to predict the future state of the atmosphere based on observations of the atmosphere's initial state. Of course he performed his calculations without the aid of an electronic computer. Although he failed in his effort (his calculations predicted that weather systems would travel in the wrong direction at the speed of sound), his book, *Weather Prediction by Numerical Process*, published in 1922,

has provided a valuable introduction to the complexities of NWP for many years. An overview of the physical and mathematical basis of NWP is given in the Appendix to this memo.

The development of electronic computers in the late '40s prompted a revival of interest in NWP and led to the initiation of operational NWP in 1955. It is not surprising that weather forecasters were at first hesitant to put a lot of faith into NWP models, the first of which were very primitive (in the *negative* sense of the word):

Early models did not use the full set of *unmodified* equations (or so-called "primitive" equations in the *meteorological* sense of the word) to predict the behavior of the atmosphere. They prepared forecasts for only one level of the atmosphere (near 500 millibars). As a result, they were not able to predict changes in the intensity (development or decay) of *w e a t h e r* systems.

NWP models and electronic computers have changed dramatically since 1955. Experienced weather forecasters have come to appreciate the usefulness of NWP models and now accept them as a most valuable tool in preparing operational forecasts. Some of the improved acceptance of NWP models can perhaps be explained by a growing understanding among weather forecasters that *all* professional weather forecasts are based on *some kind* of model. Even totally subjective weather forecasts are based (consciously or unconsciously) on *conceptual models* of the atmosphere that

enable forecasters to relate operationally-important weather elements and events (e.g., temperature and heavy precipitation) to *patterns* of (1) highs, lows, and fronts on weather maps, (2) cloud features on a meteorological satellite picture, (3) reflectivity and velocity on a computer display of a Doppler radar; or to all three. Unfortunately, these models (or *rules of thumb*) are seldom documented. A branch of the science called "Artificial Intelligence" referred to as "Knowledge-Based, Expert Systems" has attempted to preserve the special knowledge contained in these conceptual models in automated computer models, with some success.

COMPONENTS OF AN NWP MODEL

The most important components of an NWP model are familiar to most weather forecasters. They include the following:

Analysis Model. An analysis model translates irregularly-spaced and sometimes sparse weather observations into a *data format* that is acceptable to the NWP model. Before spectral NWP models were invented, analysis models simply *interpolated* weather data onto the more or less regular *grid points* of models. Spectral NWP models use a series of mathematical sine and cosine functions to represent the atmospheric waves that are sampled by the weather observations. The *spectral analysis* model translates the *amplitudes* (i.e., strengths) of the various atmosphere waves into a series of *amplitudes* of the sine and cosine waves. The NWP model predicts the future amplitudes on these sine and cosine waves and then uses other mathematical functions to translate these amplitudes back into weather waves to forecast the future state of the atmosphere.

Initialization Model. The function of this aspect of an NWP model is to translate the analyzed weather data into a *physical state* that will be accepted by the NWP forecast model. The various *atmospheric states* represented by good NWP models, like the atmosphere itself, are in a *delicate state of balance*. Consequently, the *initial state* of the various atmospheric fields (e.g., temperatures and winds) presented to an NWP model must also be in this *delicately balanced state*. Indeed, NWP models are so particular about the kind of initial data they will accept that operational NWP models often take several hours of *model forecast time* to settle down before they begin producing useful weather forecasts. NWP models spend this time translating so-called "*noisy*" initial data into a *balanced state* that the model can live with. This period of time is referred to as "model spin up time." It is clear that if you want to use the first few hours of forecasts provided by an NWP model, you'll need to know the model spin up time. The question of what does and does not constitute atmospheric "noise" is a critical issue in operational NWP. We will return to this important question later in the discussion of the strengths and weaknesses of NWP models.

Numerical Components of the Model. The numerical components of an NWP model translate the *hydrodynamic* equations described in the appendix into a computer code that can be run on a modern electronic computer. Because good NWP models are nearly as complex as the atmosphere itself, the numerical components of NWP models must deal with a bewildering variety of technical issues. Many issues are so complex that the numerical components of NWP models

are usually developed by teams of meteorological and mathematical specialists. Several numerical components of NWP models have great operational significance. These include:

The Vertical and Horizontal Resolution of the Model. NWP models cannot resolve or forecast weather events that have smaller spatial scales than the effective resolution of the horizontal grid (or the "spectral" technique) used by the model. The maximum *achievable* resolution of NWP models that use grid-points is *twice the horizontal distance* between model grid points.

However, the *effective* resolution of these models is usually much less than this maximum value. The actual value depends upon several numerical aspects of the model. A good rule of thumb is that operational NWP models can resolve weather events with spatial scales equal to about four times the horizontal resolution of the models (i.e., four times the distance between horizontal grid points for a grid-point NWP model). The table below gives some idea of the spatial scale of some operationally important weather events. For a thunderstorm (20 km), model resolution would have to be 5 km (or 3 miles between grid points) to resolve this size phenomena.

Scale Definitions of Some Important Atmospheric Events

Space Scale (km)	Atmospheric Events	Remarks
> 10,000 km	Planetary atmospheric waves	Planetary waves are often apparent on 300-mb polar projection charts
2,000 to 10,000 km	Upper-atmosphere (UA) cyclone waves	These "short waves" travel through the troughs and ridges of planetary waves
200 to 2,000 km	Fronts and tropical cyclones	Position and intensity of fronts can often be subjectively inferred from patterns of UA cyclone waves
	Mesoscale convective waves	Often apparent on weather satellite and weather radar imagery
20 to 200 km	Squall lines, low-level jets, and ocean-land circulations; downslope mountain windstorms, hazardous turbulence, small-scale atmosphere waves (including gravity waves)	Episodes of strong CAT often accompany strong UA fronts

Model Boundary Conditions. Limited-area (or *window*) models require information about the weather conditions at their lateral boundaries (as well as at their upper and lower boundaries) throughout the time period forecast by the model. Global models, of course, need only upper and lower boundary conditions. Often, the boundary conditions for a window model are prepared by another NWP model. Errors associated with these boundary conditions will propagate into the interior of the model window at the speed of the fastest moving phenomena predicted by the model. This can be a big problem if the model predicts sound waves as well as weather phenomena. Fortunately, sound waves can be fairly easily excluded from NWP model predictions.

Spatial Dimensions of the Model. Operational NWP models are usually three-dimensional. Operationally useful one- and two-dimensional models are also available, but they are more difficult to use. For example, the user of a two-dimensional NWP model must figure out what is going on in the missing third dimension.

Physical Components of the Model. The physical components of an NWP model include all those components of the model that are not addressed by the *numerical* components of the model. The physical components enable the model to *take some account of (parameterize)* important physical processes that cannot be explicitly resolved by the model. These often include boundary layer processes such as evaporation cooling of the air from rain-soaked ground or radiation cooling of the ground at night under clear skies. The *parameterization* of physical processes in

NWP models is a tricky business, but the following example may clarify the process. It is possible to make a good estimate of the radiation cooling of the earth's surface by multiplying an estimate of the surface temperature, raised to the fourth power, by a constant number called the Stefan Boltzmann constant. If this rule is included in the code of an NWP model, the model can be said to have *parameterized* surface radiation cooling. Of course the goodness of this parameterization depends on the accuracy of the surface temperature forecast as well as on the goodness of the parameterization rule itself.

STRENGTHS AND WEAKNESSES OF NWP MODELS, or what NWP models can and cannot do.

The design of all NWP models involves a long list of trade-offs. In spite of their incredible complexity, the strengths and weaknesses of NWP models, as well as the operational impacts of these tradeoffs, are reasonably well documented. The most operationally significant issues can be understood from a discussion of how NWP models treat atmospheric *gravity* waves, which appear virtually everywhere in the atmosphere, caused by a combination of gravity and buoyancy forces. Buoyancy forces, of course, are responsible for cumulus clouds.

As parents of teen age sons and/or daughters know, one person's music is another person's noise. This is clearly the case in NWP. Virtually all operational NWP models (and many research NWP models) treat atmospheric gravity waves as *noise*. Indeed, many models remove atmospheric gravity waves during the initialization of the model. The *synoptic-scale* behavior of atmospheric gravity

waves seems to justify treating these waves as noise: synoptic-scale gravity waves simply serve to enhance the frictional drag on the atmosphere. However, there is mounting evidence that smaller-scale gravity waves play a crucial role in many operationally important weather events, including the initiation of severe convective storms. This multiple personality of atmospheric gravity waves can be understood by referring to the table below. As shown, synoptic-scale atmospheric gravity waves travel at nearly the

speed of sound. At these speeds, they do not have a chance to interact with the slower-moving, synoptic-scale atmospheric waves. However, small-scale gravity waves travel at speeds that are comparable to the speeds of smaller scale atmospheric waves and sensible weather phenomena (e.g., fronts). The slower speeds give these gravity waves a chance to significantly influence and modify important but smaller-scale weather phenomena.

Atmospheric Phenomena and Atmospheric Gravity Wave Speeds

Weather Phenomena	Phenomena Speeds	Gravity Wave Speeds
Planetary Waves	10 m/sec	300 m/sec
Tropospheric Cyclones	10 m/sec	150 m/sec
Fronts	20 m/sec	35 m/sec

Atmospheric gravity waves put the designers of *high-resolution* NWP models in a really difficult position.

- They can choose to eliminate gravity waves during the model initialization (by employing an appropriate model initialization scheme). However, they run the risk of degrading model forecasts of atmospheric weather events associated with gravity waves (at least during the first several hours of the model predictions--later on during the model run the model may generate its own gravity waves).
- They can choose to retain the gravity waves in the model. However, they run

the risk of having the model "blow up" because its initial state is too *noisy*--unfortunately, models have a difficult time distinguishing between the effects of real atmospheric gravity waves from *real noise* (errors) in NWP analyses due to imperfect analysis schemes and imperfect and sparse weather observations.

- They can choose to employ an initialization scheme that can accommodate the gravity waves and get rid of the real noise in the data. Clearly this is the most desirable choice. Unfortunately, available schemes substantially increase the running time of NWP models.

Appendix

THE PHYSICAL AND MATHEMATICAL FOUNDATIONS FOR NWP

NWP models embody only three physical principles: the *conservation of momentum* (wind), of *mass* (air density), and of *energy* (temperature). These principles can be expressed mathematically in:

- Three equations of air motion, which relate accelerations of the wind in the east, north, and upward directions to forces in those directions. These forces are due to pressure differences between nearby locations in the atmosphere, the rotation of the earth (the *coriolis* force), and friction.
- An *equation of continuity* which relates imports (or exports) of air into a volume to the balancing increases (or decreases) of air density in the volume.
- A *thermal* (air temperature) *energy equation*, which relates the heat energy added to a parcel of air to:
 - Increases in the *internal energy* (temperature) of the air parcel.
 - Work done by the air parcel expanding against the pressure forces of the air surrounding it.
- An *equation of state*, which relates the pressure, density, and temperature of the air parcel.

The above set of *hydrodynamic equations* comprise a complete system of six equations in six unknowns. Meteorologically, these equations provide the basis for NWP. Mathematically, they make up what is called an *initial value problem*--if one had complete knowledge of the initial state (the *initial condition*) of the atmosphere at a particular time (which of course is not possible), and if one could find a unique (i.e., single) solution to the hydrodynamic equations for this initial state, this solution would describe the future behavior of the atmosphere for *all time*--clever, yes? In practice, the equations represent a set of *non-linear*, partial differential equations for which only approximate, *numerical* solutions are known. This fact, of course, provides the basis for *Numerical Weather Prediction*. The NWP problem consists in solving (*integrating*) this system of equations based on some known initial conditions.

The *hydrodynamic equations* have been very successful in describing the behavior of many important phenomena--examples include air flow around a wing, the propagation of sound waves in the air, the propagation of ocean waves on the sea surface, and the development of a land-sea breeze on a calm summer afternoon when there is no threat of a frontal passage. These successes have prompted meteorologists and mathematicians to use these equations to predict the general behavior of the atmosphere.

The *non-linearity* of the hydrodynamic equations has a most important effect on the application of these equations in NWP. *Non-linear* phenomena are of such great significance that the systematic study of these phenomena has led to the development of an entirely new science called, "Non-linear, Dynamically Systems", or "Chaotic Systems", or simply, "*Chaos*". It is noteworthy, that the first demonstration of the unique, chaotic behavior of a *non-linear, dynamical system* (a cumulus cloud) was performed by Edward Lorenz, a meteorologist at MIT. An appreciation of the significance of the non-linear characteristics of atmospheric motions is fundamental to understanding and forecasting the behavior of the atmosphere.

Non-linear equations are easy enough to recognize:

$y = 2x + 3$ is an example of a *linear* equation.

$y = 2x + x^2 + 3$ is an example of a *non-linear* equation.

Real-world non-linear events are commonplace. Mortgage interest rates and new housing starts are an example. Lower interest rates prompt increased housing starts which in turn prompt higher interest rates. OK, but what are non-linear atmospheric motions (winds)? We can use our hydrodynamic equations to provide a quick answer to the question. If we let V represent the motion of the air in our equations (i.e., the velocity, or speed and direction, of the wind) then *any* term in the equations that contains V to a *power* higher than one (e.g., V squared) is a term that *represents* non-linear air motions. Surprisingly, only *one* term in the hydrodynamic equations is non-linear; this term describes the *advection* (or *transport*) of the air *by* the air itself. Several meteorologists have tried to describe this phenomena in words. The following colorful description has been attributed to L. F. Richardson,

Big Whirls have little Whirls that feed on their Velocity. Little Whirls have smaller Whirls, And so on to Viscosity.

A more precise description was offered by Edward Lorenz of MIT:

Because the motion of the atmosphere is not uniform, different portions of the advected motion field undergo different displacements and the field (of motion) becomes distorted.

Both descriptions describe how the air motion influences *itself*. This feedback of an *effect onto its cause* is the essence of non-linearity and is the principal cause of the incredible complexity of the atmosphere.

We can appreciate the importance of the *non-linearity* of atmospheric motions to weather forecasting by looking at two of its practical consequences.

- The most profound effect of non-linearity has to do with the *global* behavior of the atmosphere. The words attributed to L. F. Richardson above are often used to describe one theory of this behavior of the atmosphere. According to this theory:

--The abundance of solar radiation near the equator causes air to rise there in large convective cells and to ascend into the upper troposphere.

--Air travels away from the equator in the upper troposphere toward the poles (it has no other place to go).

--Air cools in its trajectory to the poles, sinks back into the lower troposphere, and eventually returns south to the equator to complete a *global circulation* of the atmosphere.

--This global circulation (a *Big Whirl*) then breaks down into *Smaller Whirls* according to the *non-linear* process described by Richardson: "Big Whirls (the general circulation) have little Whirls (mid-latitude cyclones) that feed on their Velocity. Little Whirls have smaller Whirls (turbulence), And so on to Viscosity (friction)."

This concept is important because it offers a practical (albeit imperfect) basis for translating NWP forecasts into weather forecasts. This concept is based on assumptions that:

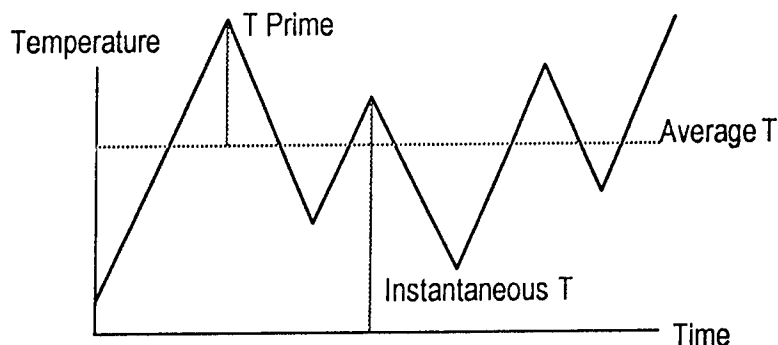
--Operational NWP models provide good forecasts of the behavior of the *big whirls* (e.g., 500 mb, synoptic scale wind and temperature patterns).

--Because *little whirls* (mid-latitude cyclones) mainly feed on the velocity of *big whirls* (i.e., are mainly due to the cascade of energy, down-scale, from the *big whirls* to *smaller whirls*):

--The behavior of the *little whirls* and their associated weather cyclones and fronts can be inferred from NWP forecasts of the *big whirls* using conceptual models developed in Norway and the United States during WWII and the early fifties.

--Forecasts of the weather associated with the cyclones and fronts can be inferred from the same class of conceptual models.

- The second consequence of the non-linearity of atmospheric motions helps explain the fundamental limitations of NWP models in general and the limitations of the latter approach to using operational NWP models to prepare weather forecasts. This effect of the non-linearity of our equations is rooted in the fact that any application of these equations (e.g., to predict the weather) constitutes an *initial value problem*. When the equations are used to predict the weather, they (the equations) assume that the initial values they are given represent the *real initial conditions* of the atmosphere at a particular instant in time. Since weather observations represent an average value over some time period, we must modify our equations to take this fact into account. We can understand how this is done by referring to the following diagram.



As the diagram shows, we may replace the instantaneous Temperature (T) at a particular instant by the *sum* of the average T over a time period that includes that instant, and the *difference between the average T and the instantaneous T at that instant* (often called T Prime).

We can use this rule to replace *all* the occurrences of our original *instantaneous* unknowns with the new unknowns that include the desired *average values* of our unknowns. Our new NWP equations are now ready to accept real data derived from real weather observations.

So what do our new *averaged* NWP equations look like? At first glance, they look exactly like our original equations--except that the *instantaneous* unknowns have been replaced with the new *average value* unknowns. However, upon closer inspection, we find that the equations now contain new terms that contain the products of the *primed* unknowns introduced above. If we took the trouble to track down where these new terms came from we would discover (as you might guess) that they are produced by the *non-linear terms* in our equations. If we would investigate the physical significance of these new terms, we would find that they represent the effects of the *non-linear interactions of atmospheric motions*. Meteorologists have come to call this phenomena "atmospheric turbulence."

This is the same turbulence that causes evaporation of water in a lake (*garden variety* turbulence) and the turbulence that threatens the safety of aircraft (e.g. *severe or extreme clear air turbulence*). These turbulence processes are also responsible for many operationally significant weather events that are not predicted by operational NWP models. An example is radiation fog (fog caused by radiation cooling of the ground at night). Most of the physical processes responsible for radiation fog can be modeled by the turbulence expressions described above. These processes include the cooling and drying (or moistening) of air near the surface by the turbulent mixing of the air in the boundary layer. It is relatively easy to build a simple forecast model for atmospheric radiation fog by combining a model of radiation cooling of the surface with a model of the above turbulence mixing processes (we have developed a prototype of such a model at HQ AWS/XTX). But if this is the case, why are such models not available to operational weather forecasters? These models are more difficult to use than all-purpose, three-dimensional operational NWP models because they put the *weather forecaster* in the position of having to decide when it is and when it is not appropriate to use them. Therefore, forecasters must have a really good understanding of the technical capabilities and limitations of this or any model--a tough and time-consuming effort.

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USAFALCENT RA, Pope AFB, NC 28308-5000	1	90 OSS/DOW, 7505 Saber Rd., Bldg 1250, F.E. Warren AFB, WY 82001-5000	1
CCSO/FL, Tinker AFB, OK 73145-6340	1	55 OSS/DOW, 509 SAC Blvd, Ste 1, Bldg T29, Offutt AFB, NE 68113-2094	1
304 ARRS/DOOR, Portland IAP, OR 97218-2797	1	93 OSS/DOW, 7th St., Bldg 1340, Castle AFB, CA 95342-5000	1
AFOSR/NL, Bolling AFB, DC 20332-5000	1	92 OSS/DOW, Bldg 1, Fairchild AFB, WA 99011-5000	1
TFWC/WE, Nellis AFB, NV 89191-5000	1	43 OSS/DOW, Ave D, Bldg 360, Malmstrom AFB, MT 59402-5000	1
AMC/XOWR, Bldg P40 N, Martin Ave, Scott AFB, IL 62225-5000	1	9 OSS/DOW, Gruman Ave., Bldg 1060, Beale AFB, CA 95903-5000	1
438 OSS/WXF, Bldg 1730, Vandenberg Ave., McGuire AFB, NJ 08641-5000	1	96 OSS/DOW, Base Ops Rd., Bldg 9001, Dyess AFB, TX 79607-5000	1
89 OSS/WXF, Operations Dr., Bldg 1220, Andrews AFB, MD 20331-5000	1	5 OSS/DOW, 221 Flight Line Dr., Bldg 746, Minot AFB, ND 58705-5021	1
437 OSS/SSW, Hill Blvd, Bldg 162, Charleston AFB, SC 29404-5000	1	384 OSS/DOW, Kansas Ct., Ste 104, Bldg 1112, McConnell AFB, KS 67221-5000	1
436 OSS/WXF, Bldg 501, Eagle Way St B, Dover AFB, DE 19902-5987	1	2 WS/CC, Bldg 5546, 245 Davis Ave, Barksdale AFB, LA 71110-5002	1
230SS/OSW, Bldg 708, Pope AFB, NC 28308-5000	1	42 OSS/DOW, Georgia Rd., Bldg 8200, Rm 10, Loring AFB, ME 04751-5000	1
60 OSS/WX, 611 E St., Bldg P4, Travis AFB, CA 94535-5024	1	416 OSS/OSW, 582 Bangor Rd., Ste 121, Bldg 1000, Griffiss AFB, NY 13441-5000	1
443 OSS/WXF, Bldg 185, Rm 123, Ave E, Altus AFB, OK 73523-5987	1	380 OSS/DOW, Alabama Ave., Bldg 2712, Rm 100, Plattsburgh AFB, NY 12903-5000	1
375WS/OGWB, Bldg 433, Scott AFB, IL 62225-5000	1	319 OSS/DOW, 695 Steen Ave., Bldg 528, Ste 106, Grand Forks AFB, ND 58205-6244	1
62 OSS/WXF, Bldg 1172, McChord AFB, WA 98438-5987	1	28 OSS/OSAW, Bldg 7506, Ellsworth AFB, SD 57706-5000	1
63 OSS/OSW, Bldg 795, Norton AFB, CA 92409-5987	1	351 OSS/DOW, Bldg S35, Whiteman AFB, MO 65305-5000	1
314 OSS/OSW, 1st St., Bldg 120, Little Rock AFB, AR 72099-5000	1	7 OSS/DOW, Bldg 1425, Carswell AFB, TX 76127-5000	1
542 OSS/WXF, Kirtland AFB, NM 87117-5987	1	410 OSS/DOW, F Ave., Bldg 401, Ste 7, K.I. Sawyer AFB, MI 49843-3400	1
1SOW/OGSW, Attn: Lt Kelly, 150 Bennett, Bldg 90730, Hurlburt Field, FL 32544-5000	1	305 OSS/DOW, Hoosier Blvd, Bldg S-28, Grissom AFB, IN 46971-5000	1
AFSOC/DOW, Hurlburt AFB, FL 32544-5000	1	379 OSS/DOW, Operations St., Bldg P14, Wurtsmith AFB, MI 48753-5000	1
ATC/DOTW, Bldg 399, Rm B27, D St., East, Randolph AFB, TX 78150-5000	1	ACC/DOW, Bldg 21, 30 Elm St, Ste 215, Langley AFB, VA 23655-2093	1
12OSS/DOW, Bldg 8, S St. East, Randolph AFB, TX 78150-5000	1	24WS, Unit 0640, APO AA 34001-5000	1
14OSS/DOW, 1st St., Bldg 857, Columbus AFB, MS 39701-5000	1	9COS/AOSW, Bldg 1130, Shaw Dr., Shaw AFB, SC 29152-5410	1
323OSS/DOW, H and 6th St., Bldg 4579, Mather AFB, CA 95655-5000	1	OL-A, 363FW/DOMS, RFD 1, McEntire ANGB, Eastover, SC 29044-9690	1
640SS/DOW, Bldg 79, Reese AFB, TX 79489-5000	1	4 Operations Group/OSW, 1980 Curtiss Ave., Ste 140, Bldg 4507, Seymour Johnson AFB, NC 27531-2524	1
80OSS, J Ave., Bldg 1360, Step 235, Sheppard AFB, TX 76311-5000	1	354 FW/DOM, 1st St., Bldg 362, Myrtle Beach AFB, SC 29579-5000	1
71OSS/DOW, Elam Rd., Bldg 155, Vance AFB, OK 73705-5000	1		
100FTS/DOW, Front St., Bldg S19, Williams AFB, AZ 85240-6497	1		

23 FW/WE, England AFB, LA 71311-5000	1	Det 11, 7WS, Coleman Bks Wea, Unit 29719, APO AE 09028-3728	1
31 OSS/OSW, Coral Sea Blvd, Bldg 702, Homestead AFB, FL 33839-5010	1	Det 12, 7WS, Unit 24220, APO AE 09185-5000	1
1 OG/WS, Flightline Ave., Bldg 754, Langley AFB, VA 23665-5508	1	OL-A, Det 12, 7WS, APO AE 09111-5000	1
325 OSS/OSW, Stop 22, Tyndall AFB, FL 32403-5048	1	Det 13, 7WS, Cmr 416, APO AE 09140-9998	1
347 OSS/OSW, Savannah St., Bldg 622, Moody AFB, GA 31699-5000	1	Det 26, 7WS, Unit 29632, APO AE 09096-5000	1
56 OSS/OSW, Bldg P3, Rm 101, Florida Ave., McDill AFB, FL 33608-5000	1	435OSS/DOW, APO AE 09097-5000	1
12AOG/AOSW, E Ave., Bldg 2900, Bergstrom AFB, TX 78743-5000	1	81 TFW/WE, Unit 5975, APO AE 09497-5000	1
27 OSS/OSW, 110 E Sextant Ave., Ste 1040, Cannon AFB, NM 88103-5322	1	20OSS/DOM, Unit 5475, APO AE 09466-5000	1
355 OSS/OSWF, Phoenix St., Bldg 4820, Davis-Monthan AFB, AZ 85707-6801	1	10 TFW/DOM, Unit 5685, APO AE 09470-5000	1
49 OSS/OSW, Bldg 571, Holloman AFB, NM 88330-5000	1	32OSS/WE, Unit 6795, APO AE 09719-5000	1
58 OSS/OSW, 8th St., Bldg 953, Luke AFB, AZ 85309-5000	1	86WF, Unit 3090, APO AE 09094-5000	1
OL-A 58OSS/OSW, Bldg 324, Gila Bend AFAF, AZ 85337-5000	1	40 SW/WX, Unit 6160, APO AE 09601-5000	1
57 OSS/OSW, 27 Depot Rd., Bldg 805, Nellis AFB, NV 89191-5000	1	52 OSS/WEF, Unit 3720, Box 195, APO AE 09126-5000	1
366 OSS/OSW, 655 Oak St., Mt Home AFB, ID 83648-5000	1	16AF/SWO, Unit 6365, APO AE 09641-5000	1
24WS/CC, APO AA 34001-5000	1	401 CSG/WE, Unit 6490, APO AE 09641-5000	1
ATSI/CDW, US Army Intel, Ft Huachuca AI, AZ 85613-5000	1	39 TACG/DOM, Unit 7090, Box 115, APO AE 09824-5000	1
129 ARRS/DOV, NAS Moffett Fld, CA 94035-5006	1	52TFW/JOTM, APO AE 09705-5000	1
USCENTCOM/CCJ3-W, MacDill AFB, FL 33608-7001	1	OL-C, 7WS, CMR445, Box 260, APO AE 09046-5000	1
USSOCENT/SCJ2-SWO, MacDill AFB, FL 33608-7001	1	48 Weather Flight, APO AE 09464-5000	1
USSOCOM/SOJ3-W, MacDill AFB, FL 33608-6001	1	105 Weather Flight, Tennessee Air National Guard, PO Box 17267,	
Det 1, NEADS/DOW, Maineiac Ave., Bldg 510, Bangor ANGB, ME 04401-3099	1	Nashville, TN 37167-2091	1
101 AREFW/DO, Bangor ANGB, ME 04401-3099	1	107 Weather Flight, Selfridge ANGB, MI 48045-5024	1
1WG, Bldg 168, Hardee St., Ft McPherson, GA 30300-5000	1	110 Weather Flight, MO ANG, 131TFW, Bridgeton, MO 63044-2371	1
OL-A, 5WS, AFZJ/SWO, Ft Irwin, CA 92310-3000	1	111 Weather Flight, Ellington ANGB, TX 77034-5586	1
Det 1, 1WXG, Bldg 7163, Ft Campbell, KY 42223-5000	1	113 Weather Flight, Hulman Fld, Terre Haute, IN 47830-5000	1
Det 2, 5WS, Davison USA Airfield, Ft Belvoir, VA 22060-5746	1	116 Weather Flight, WA ANG, Bldg 304, McChord AFB, WA 98433-5000	1
OL-B, Det 2, 5WS, Ft Indiantown GAP, PA 17003-5002	1	120 Weather Flight, Buckley ANGB, CO 80011-9599	1
Det 3, 1WXG, Prager St., Bldg AT3551, Ft Bragg AIN, NC 28307-5000	1	121 Weather Flight, Stop 28, Andrews AFB, MD 20331-6539	1
CDR USASOC, Attn: AOIN-ST, Ft Bragg, NC 28307-5200	1	122 Weather Flight, New Orleans NAS, LA 70143-0200	1
JSOC/Weather, P.O. Box 70239, Ft Bragg, NC 28307-5000	1	123 Weather Flight, Portland IAP, OR 97218-2797	1
Det 4/WXG, Hangar Access Dr., Bldg 2065, Ft Drum, NY 13602-5042	1	125 Weather Flight, PO Box 580340, Tulsa AFS, OK 74158-0340	1
Det 5, 1WXG, Bldg 5220, PO Box 940, Ft Knox, KY 40121-5540	1	126 Weather Flight, WIANG, 350 E College, Milwaukee, WI 53207-6298	1
Det 6, 1WXG, Bldg 3082, Airport Dr., Ft Lewis, WA 98433-5000	1	127 Weather Flight, Forbes Fld, Topeka, KS 66619-5000	1
Det 7, 1WXG, Bldg 518, Ritchie AAF, Ft Ord, CA 93941-5111	1	130 Weather Flight, Yeager Apt, Charleston, WV 25311-5000	1
Det 8, 1WXG, 743 Ray Place, Bldg 743, Ft Riley, KS 66442-5317	1	131 Weather Flight, Barnes Map, Westfield, MA 01085-1385	1
OL-A, Det 8/WXG, Forney AAF, Bldg 5004, Ft Leonard Wood, MO 65473-5862	1	140 Weather Flight, Willow Grove NAS, PA 19090-5105	1
Det 9, 5WS, Ft Rucker, AL 36362-5162	1	146 Weather Flight, GTR Pittsburg ANG AN, PA 15231-0459	1
OL-A, Det 9, 5WS, Rt 3, Box 302, Troy, AL 36081-5000	1	154 Weather Flight, Camp Robinson, North Little Rock, AR 72118-2200	1
Det 10, 1WG, Bldg 2485, Rm 110, Lawson AAF, Ft Benning, GA 31905-6034	1	156 Weather Flight, 5225 Morris Fld Dr., Charlotte, NC 28208-5797	1
75th RGR (Attn: SWO), Ft Benning, GA 31905-5000	1	159 Weather Flight, c/o HQ FLANG, State Arsenal, St Augustine, FL 32085-10081	1
Det 11, 1WXF, Post Rd., Bldg 4907, Ft Sill, OK 73503-5100	1	164 Weather Flight, Rickenbacker ANGB, OH 43217-5007	1
Det 12, 1WXG, Bldg 860, Ft Devens, MA 01433-5310	1	165 Weather Flight, Standiford Fld, Louisville, KY 40213-2678	1
Det 13, 1WXG, Condon Rd., Bldg 2408, Ft Eustis, VA 23604-5252	1	181 Weather Flight, 8150 W Jefferson Biv, Dallas, TX 75211-9570	1
Det 14, 1WXG, Bldg 90049, Rm 118, Gray AAF, W Ft Hood, TX 76544-5076	1	195 Weather Flight, 4146 Naval Air Rd., Port Huenene, CA 93041-4001	1
OL-A, Det 14, 1WXF, Slewitzke St., Bldg 11210, Ft Bliss, TX 79916-2418	1	199 Weather Flight, Wheeler AFB, HI 96854-5000	1
OL-A, Det 21, 1 WXG, Stranch St, Bldg 1252, Hunter AAF, GA 31409-5193	1	200 Weather Flight, 5680 Beulah Rd., Sandston, VA 23150-8109	1
Det 31, 1WXG, Ft Polk AAF, Bldg 9226, Ft Polk, LA 71459-6250	1	202 Weather Flight, Otis ANGB, MA 02542-5028	1
Det 58, 1WXG, Bldg 9601, Butts AAF, Ft Carson, CO 80913-6403	1	203 Weather Flight, Ft Indiantown GAP, Annville, PA 17003-5002	1
USAFE/DOW, Unit 3050, Box 15, APO AE 09094-5000	1	204 Weather Flight, McGuire AFB, NJ 08641-6004	1
17AF/DOW, Unit 4065, APO AE 09136-5000	1	207 Weather Flight, 3556 N. Michigan Rd., Shelbyville, IN 46176-4914	1
Det 1, 86 OPS GP, Unit 8495, APO AE 09094-5000	1	208 Weather Flight, 206 Airport DE, St Paul, MN 55107-4098	1
HQ USEUCOM ECJ3, Unit 30400, Box 1000, APO AE 09128-4209	1	209 Weather Flight, PO Box 5218, Austin, TX 78763-5218	1
100 OSS/DOW, Unit 4945, APO AE 09459	1	COMNAVOCEANCOM, Code N312, Stennis Space Ctr, MS 39529-5000	2
48 OSS/WX, Unit 8300, APO AE 09464-5000	1	COMNAVOCEANCOM (Capt Brown, Code N332),	
36 TFW, Unit 3895, APO AE 09132-5000	1	Stennis Space Ctr, MS 39529-5001	1
65 AL/SS, APO AE 09720-5000	1	NAVOCEANO (Barnie Rau), Bldg 8100, Rm 203D,	
7WS, CINCUSAREUR/AREAWX, APO AE 09403-5000	1	Stennis Space Ctr, MS 39522-5001	2
7WS, Unit 29351, APO AE 09014-5000	1	WSO, H & HS Marine Station Wea, MCAS Tustin CA 92710-5000	1
OL-C, 7WS, Cmr 445, Box 260, APO AE 09046	1	TECOM, Dir for Technology, APG Met Team, Bldg 1134,	
OL-D, 7WS, Unit 23631, APO AE 09189-2764	1	Attn: AMSTE-TC-AM CAB, Aberdeen Proving Ground, MD 21005-5001	1
OL-E, 7WS, APO AE 09137-5707	1	Atmospheric Sciences Laboratory (SLCAS-AS-I 3 10-2c),	
OL-F, 7WS, Unit 31401, Box 6, APO AE 09630-5000	1	White Sands Missile Range, NM 88002-5501	1
OL-G, 7WS, Unit 22648, APO AE 09272-5000	1	TECOM Atmos Sci Div, AMSTE-TC-AA (MacBlain),	
OL-I, 7WS, Unit 26703, APO AE 09235-5000	1	White Sands Missile Range, NM 88002-5504	1
OL-J, 7WS, CMR 431, APO AE 09175-5000	1	White Sands Met Team, AMSTE-TC-AM (WS),	
Det 1, 7WS, Unit 27210, APO AE 09092-0216	1	White Sands Missile Range, NM 88002-5501	1
Det 2, 7WS, Unit 2200, APO AE 09165-9816	1	Army Missile Command, ATTN: AMSMI-RD-TE-F,	
Det 3, 7WS, Unit 29231, APO AE 09102-3737	1	Redstone Arsenal, AL 35898-5250	1
Det 4, 7WS, Unit 31020, APO AE 09025-0251	1	USATECOM, ATTN: AMSTE-TC-AM (RE) TCOM Met Team,	
Det 6, 7WS, Cmr 453, APO AE 09146-0979	1	Redstone Arsenal, AL 35898-8052	1
Det 7, 7WS, Unit 28130, APO AE 09114-5000	1	USATECOM, ATTN: AMSTE-TC-AM (AB),	
OL-A, Det 7, 7WS, Unit 28216, APO AE 09173-5000	1	Aberdeen Proving Ground, MD 21005-5001	1
Det 8, 7WS, Unit 25202, APO AE 09079-5000	1	Director, U.S.A.-CETEC, Attn: GL-AE (Whitmarsh), Fort Belvoir, VA 22060-5546	1
Det 9, 7WS, Cmr 423, APO AE 09107-0200	1	Technical Library, Dugway Proving Ground, Dugway, UT 84022-5000	1
OL-B, 7WS, Cmr 422, APO AE 09274-5000	1	HQ NATO Staff Meteorological Officer IMS/OPS APO AE 09724	1
OL-A, Det 10, 7WS, CMR454, Unit 31020, APO AE 09250-0047	1	NOAA/MASC Library MC5, 325 Broadway, Boulder, CO 80303-3328	2
Det 10, 7WS, Unit 26410, APO AE 09182-0006	1	NOAA Library-EOC4W5C4, Attn: ACQ, 6009 Executive Blvd,	
OL-B, Det 10, 7WS, APO AE 09031-5000	1	Rockville, MD 20852	1